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Eye-Tracking the City: Matching the Design of Streetscapes in High-Rise Environments with Users' Visual Experiences

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Abstract: Large cities in the West respond to an ever-increasing shortage of affordable housing by accelerating the process of urban densification. Amsterdam, for instance, aims to increase its housing stock by 10 percent in the next 15 years as its population is expected to grow by 20 percent. As in other cities, it seems inevitable that high-rise buildings with higher skyscrapers than in the past will be built within the existing urban fabric. Such large-scale (re)development projects shape the conditions for inhabitants' eye-level experiences, perception of place and overall well-being. The new hybrid field of neuroarchitecture offers promising eye-tracking technology and theories for measuring inhabitants' visual experiences of the city and rethinking the effectiveness of applied design principles across the globe. In this paper, the 'classic' design solutions for creating streetscapes on a human scale in densified areas have been assessed by eye-tracking 31 participants in a laboratory setting, all of whom viewed photographs of 15 existing streetscapes in high-rise environments. The study drew on theories from the field of neuroarchitecture and used input from a panel of (landscape) architects and urban designers to design the research and analyze the eye-tracked patterns. The results indicate that the classic design principles (horizontal-vertical rhythms and variety; active ground floor; tactile materials) play a significant role in people's appreciation of the streetscape and that their attention is unconsciously captured by the presence of these principles. The absence of the design principles seems to result in a scattered 'searching' eye-movement pattern. This also suggests that a coherent design of streetscapes in high-rise environments may contribute to a human scale at eye-level.

Keywords: Streetscapes, eye-Tracking Technology, high-rise environments, human scale, design principles

1 Introduction

The literature shows a number of risks to human well-being associated with high-rise environments. High-rise environments are related to a sense of oppressiveness (ASGARZADEH et al. 2012), and increased social isolation and societal fragmentation (SASSEN 2017). These environments are also known to have a negative impact on psychological restoration (LINDAL & HARTIG 2013) yet streets in these environments play a crucial role in the production of the social fabric (SENNETT 2018). Citizens' daily life takes place at street level and this is where the impact of densification and the presence of high-rise development play out. In this respect, it is assumed that streets are vital shared public spaces, shaped and bounded by a three-dimensional configuration of buildings and, in particular, the ground floor. Today's take on urban densification and new (extreme) high-rise require – *ex ante* – a deeper, eye-level understanding of these new streetscapes.

Since the 1960s, in response to modernism, a large number of architectural and urban design studies have researched the design attributes of streets that create liveable environments. These studies have had an impact on design practices but they have provided evidence on the relationships between the various attributes in a narrative manner. After 20 years of research

Allen Jacobs, for example, concluded that there is no standardized combination of solutions that guarantees the construction of a physical space that people appreciate and where they will linger (JACOBS 2008). A crucial factor is the *human scale of streets* (LOVENE et al. 2019), which has been emphasized and detailed in earlier influential studies (e. g.: JACOBS 1961, LYNCH 1960, CULLEN 1961, ALEXANDER et. al. 1977, GEHL 2011). JANE JACOBS (1961) pointed out the importance of mixed use, openings ('eyes on the street') and a variety of façades. These studies resulted in 'classic' design principles that were frequently implemented to create complex but structured streets. Jane Jacobs underpins this by stating that 'Intricate minglings of different uses in cities are not a form of chaos. On the contrary, they represent a complex and highly developed form of order' (p. 222). Later, PALLASMAA (2005) emphasized the importance of multiple senses for architectural design: how some shapes and textures of materials unconsciously connect with vision and bring to mind previous experiences (visual cues) such as rough, smooth and soft surfaces (see also PAPALE et al. 2016).

In the late twentieth century influential studies in the field of psychology developed theories to interpret the psychological responses to our environment. According to the overlapping Attention Restoration Theory (KAPLAN 1995) and Psycho-Evolutionary Theory (ULRICH 1984), viewing nature may have restorative effects, and nature is appreciated more than man-made surroundings. The latest eye-tracking technology offers new opportunities to examine these theories with more than 100 eye-tracking measures related to eye movement, including those related to fixation, duration, and number (HOLMQVIST et al. 2011). For instance, a high number of fixations implies a high cognitive load, which makes it difficult to process the information provided: this often occurs when subjects view urban environments (VALTCHANOV & ELLARD 2015, FRANĚK et al. 2018). When subjects view urban environments rather than natural environments, their visual exploration, measured by eye-travel distances, is higher and the duration of their fixations is shorter (VALTCHANOV & ELLARD 2015, BERTO et al. 2008, FRANĚK et al. 2018). FRANĚK et al. (2018) points out that a longer duration of fixations on features in the eye-tracking literature has been understood as more demanding cognitive processing (HOLMQVIST et al. 2011) or as points of interest, such as in face perception research.

The distinctly different results in subjects' eye-tracked patterns when viewing photographs of natural and urban environments may be explained by the level of visual complexity. Natural environments consist of moderate levels of complexity, capturing our attention and evoking *soft fascination*. The built environment, by contrast, can be highly complex, making it more difficult to capture our attention and evoking *hard fascination* (VAN DEN BERG et al. 2016, NADAL et al. 2010, VALTCHANOV & ELLARD 2015, FRANĚK et al. 2018). There is evidence that complex fractal scenes enhance our fascination (VAN DEN BERG et al. 2016, COBURN et al. 2019). Fractals are 'scale-free' patterns that tend to be produced by self-organization. Fractals applied in architecture may evoke intuitive associations with sensory features of nature (VAN DEN BERG et al. 2016, COBURN et al. 2019). The brain processes and steers the (visual) information through neural networks, operating in fractals (SAPOLSKY 2018). According to SAPOLSKY (2018), most of the time, the brain's interpretation of the scanned environment happens unconsciously. It does not take place through a linear path-dependent pattern, but is shaped by simultaneously performed associative resemblances of metaphorical similarities and physical similarities.

These cognitive responses to the environment and to architecture in particular may be further clarified by the fact that people unconsciously search for sequences in design and bilaterally

symmetrical structures in buildings (SUSSMAN & HOLLANDER 2015). NADAL et al. (2010) concludes that there are three different forms of complexity that may contribute to people's perception of complexity: (1) variety and number of elements, (2) the way they are organized (i. e. perceived as a unit) and (3) symmetry.

Today's urban densification requires renewed attention to the design of streets and the effectiveness of commonly applied design principles in the new context of high density and, in particular, high-rise environments. Only a few studies have evaluated the effectiveness of the commonly applied design principles that aim to provide a human scale in contemporary high-density settings. This calls for an in-depth analysis of these design principles using advanced eye-tracking technology.

2 Methods

2.1 Research Design

Explorative research was conducted to analyze the visual experience and perception of commonly applied design principles for new high-rise environments. Three classic design principles associated with human-scale streetscapes were selected: (1) horizontal-vertical rhythms and variety, (2) active ground floor and (3) tactile materials located in the street-façade and street-space. The aim was to explore how eye-tracking technologies can be used in an evidence-based review of applied design solutions in high-rise environments based on people's visual experiences. The empirical research was therefore combined with traditional social-science research techniques to collect and interpret data and for triangulation.

2.2 Participants

Thirty-one participants were recruited (24 males, 7 females) from the Amsterdam University of Applied Sciences. The participants were aged between 17 and 26 and most were pursuing technical studies such as aviation, mechanical engineering and product design. They participated in the study in exchange for a modest meal voucher (€ 2.50). Before the test, measures were taken to ensure that it would not be influenced by participants' impaired vision: participants who wore spectacles were excluded and those who wore contact lenses were asked if they had difficulty seeing clearly and reading from a computer screen.

2.3 Materials

The study focused on examples of streetscapes designed and built after the 1990s that reflected the application of the three 'classic' design principles. For this test, photographs were taken of streets in high-rise environments in the three largest cities in the Netherlands: Amsterdam, Rotterdam and The Hague. Fifteen images of scenes from main roads and residential streets were selected. A protocol was drawn up for taking the photographs: the aim was to reproduce, as accurately as possible, the physical conditions in streets encountered by passers-by. Following GEHL's analysis (2011) that distance from buildings and objects in the street-space play an important role in inhabitants' experience and perception, the viewpoints 'distant' and 'close-up' were selected. From a 'distant' viewpoint (14–23 metres) people are able to see the full contours of (tall) buildings whereas close up (0–5 metres), walking next to a building, people might instead experience a street's interior-exterior and height-width

ratios. The photographs were captured at a height of 1.62m, the average eye-level of the Dutch population. The photographs were taken by the AUAS crew to ensure that the protocol was followed.

Several eye-tracking studies reported the appearance of ‘disturbing’ elements that repeatedly and instantly catch the eye but are not directly relevant to the study (EHINGER et al. 2009, SUURENBOEK & SPANJAR 2018). To ensure that participants were not influenced by confounding factors, the following elements were kept to a minimum in this study: people and text (e. g. signs). The weather was checked before the photographs were taken to ensure that there would be no disturbing weather conditions like rain, fog or direct sunlight. Depending on the spatial situation, photographs were taken using the following proportions: 1/3 street-façade left, 1/3 street-space and 1/3 street-façade right or 2/3 street-façade and 1/3 street-space. All of the photographs were resized to 1920 x 1080 pixel resolution and they were not digitally modified (i. e. photoshopped).

2.4 Procedure

Before the test, a panel of 14 experts were commissioned to classify each photograph according to the presence and quality of three design principles: horizontal-vertical rhythm and variety, active ground floor, and use of tactile materials. Using their expertise in architecture, landscape architecture, planning and urban design, the experts were separated into two groups to categorize the photographs. When the photographs had been categorized, they were swapped between the groups to validate the results. If there was consensus on the categorization of a photograph, it was categorized according to the ‘presence’ or ‘absence’ of a single design principle. Afterwards, an overall categorization of the presence of the three design principles per scene was made (see Table 1). If no agreement was reached on the application of a design principle, it was classified as ‘ambiguous’.

The laboratory tests were performed in a closed-off room. Each participant was told that he/she was participating in a study on the future of the city and that eye-tracking technology would be used to record their visual experiences while they viewed a series of images. In the experiment, a Tobii x2-30 compact bar eye-tracker was used together with Sony WH-1000XMS3 headphones with noise-cancelling to ensure that noise was kept to a minimum. The images were shown on a 1920 x 1080 pixels screen (full screen), positioned at eye-level with a distance of approximately 60 cm with an angle between eye-tracker and viewer. They were arranged in a slideshow and presented for 5 seconds, using Imotions version 8.1 (Visual Attention Software).

Before the viewing sessions started, each participant underwent a process of eye-tracking calibration and was informed about the duration of the test. At the start of the test participants were placed in front of a grey screen with questions regarding their background. They were asked to type in details such as their home town, age and course of study. They were given the following instruction: Please open up the environments you are going to see in a moment. After each image, a grey screen displayed a single question in Dutch: Would you like to see yourself walking down this street? (English translation). Using a Likert scale from 1–5, the participants responded to the question by ticking the box that corresponded with strongly disagree (1), disagree (2), neither agree nor disagree (3), agree (4) or strongly agree (5). After the participant had ticked the box, a black screen was displayed for 2 seconds to ensure that the next scene would not be influenced by the previous scene.

3 Results

For every image, each participant's eye-tracked data were processed, aggregated and represented as heatmaps using Imotions software. The heatmaps showed the scan paths followed by the participants' combined eye-fixations over a five-second period. The data collected and analyzed from three different sources (expert panel, eye-tracked data and survey) were structured according to the order of the images. The metadata was analyzed using an empirical visual data analysis. The analysis focused on the first two seconds: based on other eye-tracking studies (CALVO & LANG 2004, SUURENBROEK & SPANJAR 2018), it was assumed that this short time frame mostly consists of unconscious visual scanning behaviour. The aggregated video clips were analyzed per image in order to understand the full range of eye-movement dynamics. The 15 images categorized by the expert panel and the survey of participants' appreciation were used to analyze users' visual experiences according to the presence/absence of design principle(s) in each scene.

3.1 General Eye-Tracked Patterns

For all of the scenes viewed, the aggregated data repeatedly showed a specific eye-movement pattern (see Fig. 1) during the different time frames. In 11 images the pattern was strong, and in 4 it was less pronounced, probably due to specific spatial features (the presence of vehicles, people, text etc.), but nevertheless present. In general, participants started to 'look' towards

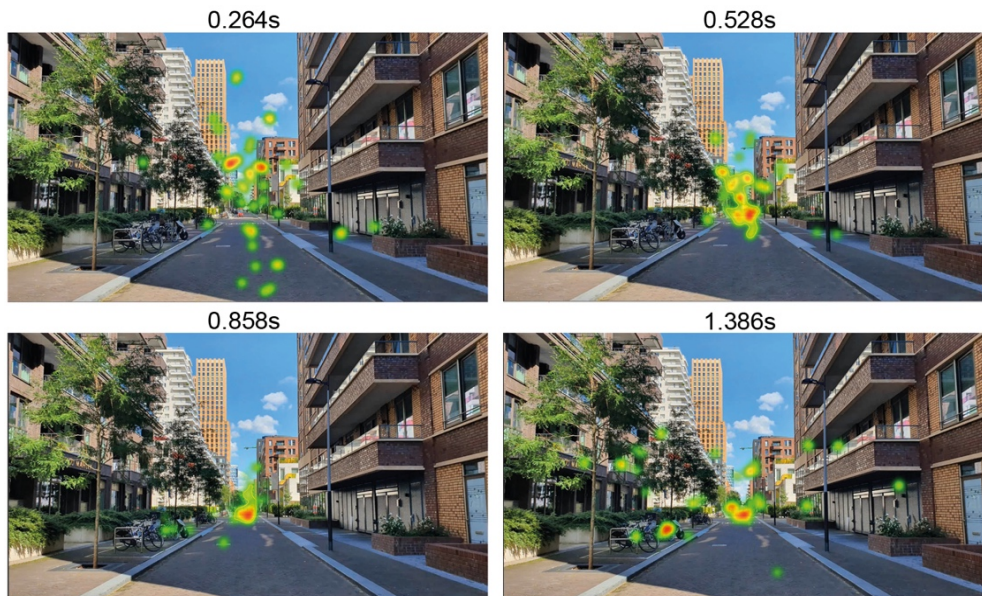


Fig. 1: Aggregated heatmap of George Gershwinlaan, Amsterdam, using eye-tracked data collected from 31 participants. It shows the eye-movement dynamics from the start, with eye-fixations centring along a vertical area of interest (top left); clustered towards the end of the street (top right); and strong central fixation (bottom left) developing into horizontal exploration of the scene (bottom right).

the centre of the scene; combining all of the participants' eye-fixations, this created a 'vertical line', i. e. a vertical focus area. In the next time frame, their fixations returned to the centre of the scene, but this time they were more clustered, around the vanishing point and/or end of the street. After this time frame, the pattern changed: the fixations on the scene were spread more horizontally. In general, after 2 seconds the eye-movement pattern seemed to continue as a more limited form of visual engagement.

In line with other eye-tracking studies (EHINGER et al. 2009, SUURENBOEK & SPANJAR 2018), the presence of people inevitably drew the participants' visual attention. This was the case even if they were in a less dominant position such as in the background (12 out of 13 scenes with people) or absent from locations where people might have been expected: balconies, large windows and open ground floor. These places were immediately scanned in the first second and repeatedly revisited during the following seconds. The same holds for the scanning of letters, numbers and all other forms of readable objects (13 scenes showed letters and numbers). However, these were generally not scanned in the first half second, but shortly afterwards. Even where letters were anticipated but were unreadable or absent – shops signs, for example, and bus stops – people's eyes fixated on these points. In 14 scenes vehicles such as cars, scooters and bicycles triggered people's eye-fixation. Participants also tended to scan the end of the street or the horizon (see Fig. 1), as well as the fragments of the streetscape that were harder to 'read', sometimes due to their contrast with the shape of the streetscape in the foreground.

Table 1: Participants' appreciation of the scenes and experts' categorization of images according to the appearance of the design principles

Street №	Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Mean	Appearance
1	0	0	7	23	2	3.8	Positive
2	0	6	17	7	1	3.1	Ambiguous
3	2	12	13	3	1	2.6	Ambiguous
4	0	7	13	9	2	3.2	Negative
5	0	1	16	12	2	3.5	Positive
6	0	1	7	21	2	3.8	No consensus
7	3	5	14	9	0	2.9	Ambiguous
8	0	1	6	21	3	3.8	Positive
9	0	4	11	12	4	3.5	No consensus
10	0	1	8	18	4	3.8	Positive
11	0	3	7	20	1	3.6	No consensus
12	0	3	11	16	1	3.5	Positive
13	0	3	3	21	4	3.8	Positive
14	3	8	13	7	0	2.8	Ambiguous
15	1	15	13	2	0	2.5	Negative

For 12 out of a total of 15 scenes, participants' responses corresponded with the experts' categorization of the streetscapes according to the presence or absence of design principles. For example, if a scene had been categorized as 'positive' for the appearance of the design principles, the participants' responses were correspondingly positive when asked: Would you like to see yourself walking down this street and the same was the? The experts did not reach consensus on the presence or absence of the design principles for 3 of the 15 scenes (see Table 1), and they were uncertain about 4 scenes. The scene shown in Figure 1 (Street No. 1 in Table 1), received the highest appreciation score: 23 participants agreed and 2 strongly agreed with the statement that they would like to see themselves walk down that specific street. The highest appreciation value was in line with the panel of experts' categorization. There was a high variation in buildings (left and right) and although there was no active ground floor (2), the appropriate size together with the row of trees (3) suggests a human scale. The eye-tracked pattern shows an exploration from the horizon towards the balconies of several buildings.

3.2 Empirical Analysis

When comparing four streetscapes with similar viewpoints and spatial settings, the role played by the applied design principles becomes clearer (see Fig. 2). The experts agreed that the first street (see Fig. 2A) showed an active ground floor that was nevertheless perceived as anonymous and lacking in variation and rhythm. A level of plasticity and the use of tactile materials were apparent in the street-space due to a sequence of benches and plants.

The participants' levels of appreciation also varied when, for example, they were asked if they agreed that they would like to see themselves walk down the street: 6 disagreed, 17 were neutral, 7 agreed and 1 strongly agreed. People fixated in the first half second on the ground floor in the background, where the roof and façade meet. Signs and the mannequin displayed in the window caught the attention shortly afterwards. Between 1 and 2 seconds, participants fixated more on buildings on the other side of the street and, in particular, on a large red billboard with small text in the distance.

In the street shown in Figure 2B, the experts agreed that there was no active ground floor. The façade, like the street-space, was described as 'monotonous' and lacking in variation. The experts used the label 'little use of tactile materials' to describe the scene. The participants were asked if they agreed with the statement that they would like to see themselves walk down this street: 9 participants agreed, 2 strongly agreed, 7 disagreed and 13 were neutral. In the first half second, the openings on the ground floor instantly captured the viewers' attention. This was followed by an exploration of the street-space and fixations on the passerby and on the signboard. Between 1 and 2 seconds, participants revisited the ground floor, in particular the opening in the forefront and the reflection of the street-space next to it.

The experts found it difficult to agree on whether the building in the forefront of the street in Figure 2C had an active ground floor, but they agreed on the appearance of the vertical rhythm and the presence of some tactile material in the street-space. Participants appreciated this scene (12 agreed with the statement that they would like to see themselves walk down the street, 2 strongly agreed and 1 disagreed), although there was a significant group that neither agreed nor disagreed (16). In the first half second, the participants fixated on the ground floor and, later, on the end of the street and on several signs. Between 1 and 2 seconds, some eyes fixated on the façades of the buildings on the right side of the street, but most (re)visited the windows and doors on the ground floor.

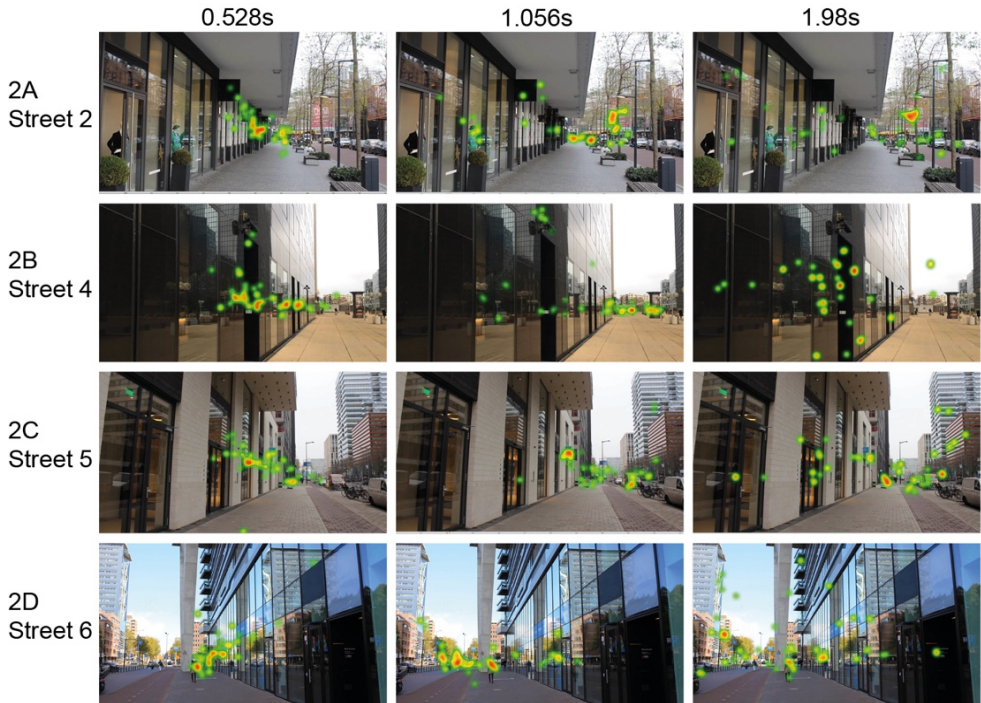


Fig. 2: Four streets with similar viewpoints and spatial settings with aggregated eye-tracked data from 31 participants, presented as heatmaps with 3 time frames

In the fourth street (Fig. 2D), experts agreed that there was no variation in the ground floor or in the streetscape. They also agreed that the height of the ground floor made it difficult to create a human scale. However, participants were positive about this scene: 21 agreed, 2 strongly agreed, 7 were neutral and 1 disagreed with the statement that they would like to see themselves walk down this street. The sleek material used for this building's skin reflected the blue sky and instantly captured several participants' attention; this was followed by a pattern of eye-movements along the ground floor and past the passer-by to the end of the street. After one second, the participants explored both the contours of the buildings on the other side of the street and (re)visited the ground floor of the building in the forefront, with some fixation on the balconies.

4 Discussion

The results showed that in the high-density environments that were assessed, the commonly applied design principles tend to capture participants' visual attention (unconscious scanning – roughly the first 2 seconds) and possibly guide their visual attention (conscious looking).

Streets where all three design principles were applied, such as in Figure 1, were highly appreciated by the participants. Their eyes fixated on the ground floor, and on the variety in the façade such as on (oriel) windows and balconies – what Jane Jacobs referred to in 1961 as

‘eyes on the street’. The panel of experts praised the level of detail in these scenes: the cobblestones, for example, and raised stone flowerbeds that create a subtle transition between the façades and the street-space, softening the effect of high-rise buildings and placing green in the user’s primary view. The absence of (any of) the three design principles, such as active ground floors, appears to result in much more scattered ‘searching’ patterns. Remarkably, whether a ground floor is closed or transparent has little effect on eye-fixation: rhythm disappears and façades only draw attention because of openings or the reflection of the street-space in façades (see Fig. 2). The visual experience might be affected by the controlled perspective. For instance, whether a ground floor is in the foreground or in the distance might determine the level of reflection and transparency. The results partly resonate with earlier findings that highly ornate, detailed buildings are viewed longer (VAN DEN BERG et al. 2016). This confirms observations by NADAL et al. 2010 and VALTCHANOV & ELLARD 2015 that a moderate level of (urban) complexity is recommendable. A coherent streetscape design that uses the design principles discussed above may contribute to this at eye-level.

Further research is needed to confirm these preliminary findings. This research should use the literature on the classic design principles (e. g. ALEXANDER 1977, GEHL 2006) to formulate hypotheses concerning the systematic reduction of variables in the eye-fixation patterns in relation to the design principles applied. How do moderate levels of complexity impact the cognitive processing of spatial information in order to give form in the design process? More interdisciplinary research is required, drawing on expertise from the fields of neurology and psychology in order to integrate non-linear fractal brain and environmental processes (SAPOLSKY 2018). More attention should be paid to the confounding variables and how they can be controlled. Despite attempts to limit the appearance of people and typography in the images they still steer participants’ visual experiences. On the other hand, it could be argued that shop and traffic signs in the streetscape should be treated as components of the applied design principles and the presence of people as a result. However, understanding the role of people in particular streetscapes might best be researched using other, complementary methodologies (e. g. behaviour observations or surveys).

Researchers using eye-tracking techniques in a laboratory setting face obstacles similar to those they face when using conventional methods in a laboratory: bias is easily created by factors such as participants’ social expectations, their awareness of the test, cultural perceptions, etc. The lack of a comprehensive research design to articulate transparency and describe the limitations regarding ‘natural’ conditions might severely compromise the outcomes of the test. Similarly, using mobile eye-tracking technology and conducting tests in a real-world setting will not ensure bias-free tests. In the current study, the inclusion of people in inconspicuous positions in the streetscape images increased the complexity of visual analysis; in a real-world setting it probably becomes even more complex. Further, SCOTT et al. (2017) argues that in an outdoor environment the visual stimuli observed by participants change constantly, creating the risk that each participant might view a different scene. The advantage of conducting tests in a laboratory setting is that confounding factors such as people, sounds, animals, weather conditions, traffic, smells, colours, typography, viewpoint, etc. can be controlled as much as possible.

Another challenge is how to use images to represent the behaviour of passers-by. One solution might be to mimic movement using a sequence of images or ‘controlled’ video recordings to ensure the same level of perspective. Another solution might be to conduct mobile eye-tracking in a real-world setting. Each method has its advantages and disadvantages. The

various eye-tracking methods should be the subject of in-depth comparative research. The focus should be on whether all factors that unequally contribute to the visual experience of the built environment in a real-world (spatial) setting are incorporated into the laboratory setting in order to validate commonly used laboratory set-ups. Video clips of aggregated eye-movement patterns for instance, are able to capture the full eye-movement dynamics. In this study, they revealed a specific pattern for the streetscapes: the participants' eyes fixate first on one specific position, vertically in the centre, and their fixations then spread and the pattern develops horizontally. After approximately two seconds, there appears to be a continuation of or a revisit to earlier areas of interest. This hints at a shift from subconsciously scanning the environment to conscious visual engagement. However, more research with a larger sample size, more scenes and increased complexity is needed to confirm these results. Future eye tracking research should focus on gaining a deeper understanding of the general scan patterns and of how designed urban spaces influence users' visual experiences.

5 Conclusion and Outlook

Today's extreme urban densification across the globe calls for more substantial research into the possible effects of design solutions at street-level. The panel of commissioned experts stressed the importance of paying more attention to the design of the street-space itself in the design process for new high-rise developments. Many of the street-spaces in the 15 photographs seemed to have been designed primarily for mobility and safety (e. g. to separate cars from pedestrians).

Emerging biometric technology and processing software from the field of neuroarchitecture open up new possibilities to reach a deeper understanding of how commonly used design principles are experienced in the built environment. In particular, the new generation of eye-tracking technology has the potential to make a valuable contribution to the evaluation of design solutions in existing built environments. This will make it possible to match future designs with people's experiences. Neuroarchitecture is still in its early stages but its expanding interdisciplinary knowledge and technology can be tailored to individual design processes. Each design project requires a situational approach but over time neuroarchitecture may deliver valuable biometric guidelines and technology for (landscape) architects to enhance their design practices.

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